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Cold Kaons from Hot Fireballs

Volker Koch

Physics Department, State University of New York
Stony Brook, NY 11794, U.S.A.

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Abstract

The E814-collaboration has found a component of very low m_t K^+ mesons with a slope parameter of $T \sim 15\,\mathrm{MeV}$. We will present a scenario which explains the observed slope parameter and which allows us to predict the expected slope parameter for kaons produced in heavier systems such as Au+Au. Implications for the restoration of chiral symmetry in relativistic heavy ion collisions are discussed.

1 Introduction

At quark matter '93 J. Stachel [1] presented the first data on kaon spectra obtained by the E-814 spectrometer at the AGS. These data cover only the very lowest range in m_t ($m_t - m_k \leq 25\,\mathrm{MeV}$) at somewhat forward rapidities ($2.2 \leq Y \leq 2.6$) and they can be parameterized by an exponential in m_t with a slope parameter as low as $T \simeq 15\,\mathrm{MeV}$. This slope parameter should be compared with the finding of the E-802 collaboration [2] which gives a slope-parameter of $\sim 150\,\mathrm{MeV}$ at central rapidities for values of $m_t - m > 100\,\mathrm{MeV}$. Also p-Be data, which are essentially equivalent to p-p, show a slope parameter of the order of $150\,\mathrm{MeV}$ [3]. Hence, the slope parameter found by E-814 certainly has to have its origin ion the many body dynamics of the heavy-ion collision.

A steep rise in the spectrum at low transverse momenta has also been observed for pions [2, 4, 5] . In this case the so called low p_t-enhancement can be understood by the decay of the delta resonance and event generators which include the deltas such as RQMD and ARC [6, 7] do reproduce the observed spectra very well. In case of the kaons (K^+), however, a component due to resonance decay is essentially ruled out, since there very few Phi mesons and strange anti-baryons are expected to be produced.

Another mechanism, which may lead to a cold component in the spectrum is the effect of attractive potentials as has been discussed in several papers [8, 9, 10, 11, 12]. In references [8] and [11] it was shown that the presence of an attractive mean field can affect the slope parameter of the particle spectra, in particular the high p_t part. If, however, the mean field is to affect the soft part of the spectrum, as suggested by ref. [9] for the soft pion spectrum at CERN - energy heavy ion collisions, a subtle interplay of the expansion time of the fireball and the particles under consideration is needed, as discussed in detail in ref. [12]. This relation essentially is the requirement for adiabaticity of the expansion in thermodynamics, meaning the expansion velocity has to be small compared to the velocity of the particles to be cooled. While at CERN energies the requirement for adiabaticity is not fulfilled, as demonstrated in ref. [12], at lower energies such as the Bevalac, these conditions hold and a cooling due to the mean field is possible [10].

In this note we will discuss under which circumstances an adiabatic cooling of the K^+ is possible. We will argue, that the observed very cold component in the kaon spectrum requires a rather small expansion velocity of the fireball, which, at the observed temperatures, can only be achieved if one assumes that the system initially goes through a phase with high energy density but low pressure. Such a phase is to be expected from the chiral restoration transition. As discussed in a recent analysis of lattice gauge data [13] the chiral restoration transition involves the decondensation of the gluon condensate which gives rise to an effective bag pressure of $p_{bag} \simeq -200\,\mathrm{MeV/fm}^3$. This bag- or decondensation pressure lowers the pressure of the system to very small values, nearly zero, and certainly much smaller than the 1/3 of the energy density for an ideal gas. As a consequence the

system expands much more slowly than an ideal gas, which, for temperature of the order of 150 MeV, has an expansion velocity of the order of 1/3 of the velocity of light. At this point we should also mention that the lowering of the pressure due to decondensation is inherently absent in cascade-type calculations. Those essentially simulate the behavior of an ideal gas and thus, as we will show below, predict too large an expansion velocity in order for adiabatic cooling to be effective.

Another ingredient of our model is an attractive potential for the K^+. Since the K^+N scattering amplitude is repulsive simple impulse approximation predicts a slightly repulsive optical potential in nuclear matter at zero temperature [14, 15]

$$U = \frac{-4\pi}{2m_K}(1 + \frac{m_k}{M_N})\, a_{K^+N}\, \rho \sim 25MeV \frac{\rho}{\rho_0} \tag{1}$$

where $a_{K^+N} \simeq -0.2\,\mathrm{fm}$ is the isospin averaged s-wave kaon nucleon scattering length [16]. In the framework of chiral perturbation theory [17], this potential arises from the interplay of an attractive scalar piece, which is due to explicit chiral symmetry breaking, and a repulsive vector potential as a result of vector meson exchange. If for some reason at high temperature the vector meson coupling is reduced, the resulting kaon potential could very well turn out to be attractive. Actually lattice gauge results on the behavior of the baryon number susceptibility can be understood in a hadronic framework only if the vector mesons decouple above T_c [18]. (For a more detailed discussion see [19].) It is, however, not the purpose of this article to develop yet another theory about the behavior of the K^+ in matter. We rather want to follow a phenomenological approach and determine the strength of the K^+ optical potential from the available data. As we will demonstrate in the following section, this can be done rather unambiguously within the framework of our model of collective cooling. Our result for the kaon potential should, therefore, be viewed as a phenomenological one, which then needs to be understood from underlying theoretical principles.

This article is organized as follows. In the following section we will present a schematic model of the expansion, which explains the essential physics of cooling the kaons and shows that the model parameters can be fixed from existing data. In section 3 we present results of a more microscopic calculation using relativistic transport theory [20] and we also present out prediction for the larger system $Au + Au$ after having fixed the model parameters by comparing with existing data on $Si + Au$.

2 A schematic model

It is widely accepted that in AGS collisions a hot zone consisting mainly of nucleons, deltas, and pions is being formed. In our schematic model we assume that these particles,

in particular the nucleons and deltas, give rise to an attractive potential for the kaons which follows the local baryon density

$$U(\rho(r)) \sim \rho(r) \tag{2}$$

where $\rho(r)$ is the local baryon density. As a result of the expansion of the fireball, the baryon-density and hence the potential change with time. We assume a Woods-Saxon type density profile.

$$\rho(r) \sim \frac{1}{\exp((r - r_0(t))/\Delta(t)) + 1} \tag{3}$$

so that the potential has the following form

$$U(r) = \frac{U_0}{\exp((r - r_0(t))/\Delta(t)) + 1} \tag{4}$$

The expansion of the fireball is then modeled by increasing the radius r_0 and the surface thickness Δ as a function of time.

$$\begin{aligned} r_0(t) &= r_0(t=0) + \frac{t}{\tau} \\ \Delta(t) &= \Delta(t=0)\frac{r_0(t)}{r_0(t=0)} \\ U_0(t) &= U_0(t=0)\left(\frac{r_0(t=0)}{r_0(t)}\right)^3 \end{aligned} \tag{5}$$

where $v = 1/\tau$ is the expansion velocity. By scaling the surface thickness and the central value of the potential with the radius we ensure that the integral over the density distribution, i.e. the baryon number remains constant with time. For the Si+Au case we assume the following initial conditions for the fireball

$$\begin{aligned} R &= 3.5\,\mathrm{fm} \\ \Delta &= 1 fm \end{aligned} \tag{6}$$

The potential and its time dependence is then determined from eq. (2) using the above density function.

While the motion of the baryons and the resulting mean field potential for the kaons is modeled by the time dependence of the density distribution, the propagation of the kaons in the potential is treated explicitly by solving the appropriate semiclassical Vlasov equation. As it is common practice in the BUU/VUU type (see. e.g. [20], [21]) transport

theoretical description, the Vlasov equation is solved by the so called test particle method, in which the phase space distribution is represented by those test particles. The solution of the Vlasov equation is then equivalent to solving classical Newton equations of motion for these test particles in the potential given above. The initial distribution of these kaon test particles follows the same density profile (3) in coordinate space. In momentum space the kaons are distributed according to a thermal Bose-distribution with temperature

$$T = 170\,\mathrm{MeV} \tag{7}$$

and zero chemical potential. In order to obtain reasonable statistics for the spectra at least 50000 test particles are needed. Since we are only interested in the shape of the spectra and not the absolute yield, a normalization of the phase space distribution is not required.

Given the above initial condition, we have two parameters left to play with, the expansion time τ and the depth of the potential U_0. As we will show, both these parameters can be fixed by comparison with the data. To this end, let us discuss their effect on the spectra. In fig. 1 we show the initial (full histogram) and the final (after expansion) spectrum at fixed potential depth of $U_0 = -50\,\mathrm{MeV}$ and for three different expansion times, $\tau = 10 fm/c$, $\tau = 5 fm/c$, and $\tau = 2.5 fm/c$. We find, that the slope at low transverse mass strongly depends on the expansion time used: the longer the expansion time the smaller the slope parameter, exactly what one expects from adiabatic expansion. The depth of the potential, on the other hand, hardly affects the slopes at low transverse mass but rather controls the number of particles contributing to the soft component of the spectrum or, equivalently, the value of the transverse mass where the spectrum changes to the initial slope. The reason why the depth of the potential hardly affects the slope at low transverse masses can be understood classically. Particles are being slowed down only by the gradient of the potential, the force, which is effective only at the surface. If the system expands too quickly, the surface moves away from the kaons, and thus cannot slow them down. If the expansion is slow, on the other hand, only those kaons which are trapped inside the potential, will be cooled adiabatically. The number of particles 'trapped' inside the potential naturally depends on the depth of the potential as only those with a kinetic energy smaller than the potential will be kept inside. Therefore, the number of particles contributing to the soft component of the spectrum is directly related to the depth of the potential. This is demonstrated in fig. 2, where we show the resulting spectra for the different potentials $U_0 = -50\,\mathrm{MeV}$, $U_0 = -100\,\mathrm{MeV}$, and $U_0 = -150\,\mathrm{MeV}$. We see that the choice of potential hardly affect the slope of the soft component.

From the above consideration it is clear, that both model parameters can be fixed from an experimental spectrum with a very low temperature component at small transverse momenta and a high temperature component at large transverse momenta. The expansion time is controlled by the slope of the low temperature component and the depth of the

potential by the position at which the spectrum changes from cold to hot. Our schematic model, of course, is not realistic enough, to compare with data. To this end, we will use a relativistic transport description [20] which takes into account the rescattering of the kaons in the fireball as well as the proper transport properties of the particles (nucleon, deltas and pions) which make up the fireball. In addition, the transport description makes sure, that the expansion of the fireball conserves energy and momentum, which has not been addressed in our schematic consideration.

3 More realistic model

In this section we want to discuss the transport theoretical calculation of the expansion and present the results for the kaon spectra. As already indicated in the introduction, ideal gas type expansion is to fast to be effective in cooling the kaons. The important slowing down of the expansion is rather a direct result of a transition through a low pressure phase which we believe is the chiral restoration transition. This leads to a softening of the equation of state and as a result the pressure, which drives the expansion, is lower than that of the ideal gas. In order to model the effect of chiral restoration or the softening of the equation of state, particles in the fireball should interact via a mean field in addition to the standard cascade type collisions. By way of that additional mean field, the equation of state can be softened. Thus, in our approach the mean field simulates the effect of chiral restoration.

The model we will use for our calculation is a relativistic transport model (see e.g. [20]), which includes nucleon, deltas, pions and kaons. The collisions among these particles are controlled by known cross sections, where for the nucleon-delta collisions an improved detailed balance method [22] has been used. For the kaon nucleon and kaon delta cross section we have assumed a value of 10 mb independent of energy. The $K^+\pi$ cross section we assume to be dominated by the K^* intermediate state and we use [23]

$$\sigma_{K^+\pi} = \frac{\sigma_0}{1 + 4(\sqrt{s} - m_{K^*})^2/\Gamma^2_{K^*}} \tag{8}$$

with $\sigma_0 = 60\,\mathrm{mb}$, $m_{K^*} = 895\,\mathrm{MeV}$, and $\Gamma = 50\,\mathrm{MeV}$.

The mean field is based on the Walecka- $(\sigma - \omega)$ model, with the possibility to include self interaction terms for the scalar field, if needed. This model has the advantage, that the necessary field (or decondensation) energy/pressure associated with a change of the gluon condensate at the chiral restoration transition [13] can be simulated by the field energy of the scalar sigma-meson at mean field level. It has also been shown, that the Walecka model shows a very rapid rise in the energy density to the value of free, massless particles at a certain critical temperature, which depends on the parameters used [24]. Of course the Walecka model is not chirally invariant and one may question whether

it is the correct tool to study the chiral phase transition. However, since at this point we are concerned only about the expansion dynamics, a mean field model which can be parameterized such that the pressure of the system is below that of an ideal gas serves this purpose. That this is possible in the Walecka model has been shown in ref. [24]. Incidentally, using the standard Walecka parameters, the scalar field gives rise to a bag-type pressure of $\sim 200\,\mathrm{MeV/fm^3}$, which is about the value extracted in the analysis of lattice calculations [13]. A more refined calculation, which addresses questions such as a temperature dependent vector coupling et c., eventually will have to be done in a chirally symmetric model.

The potential for the kaons is taken of the form

$$U_K(r) = U_0 \frac{\rho_s}{\rho_0} \tag{9}$$

where the density ρ_s is the scalar density $< \bar{\psi}\psi >$.

Thus, given the energy density as a function of temperature and chemical potential the Walecka parameters can be adjusted to reproduce that behavior of the energy density. For zero chemical potential fairly reliable and model independent information for the energy density can be extracted from lattice gauge calculations [13, 25, 26]. However, for HI collisions at presently available energies, the energy density needs to be known at finite chemical potential. Therefore, lattice results, which are restricted to vanishing chemical potential can only be used for guidance and one has to rely on model prediction of the properties of the chiral transition at finite chemical potential. Here, however, we want to follow the opposite, phenomenological approach. Rather than starting from some model input, we will try to extract the properties of the transition from the available data on kaon production. As demonstrated in the previous section, it is possible to make statements about the expansion velocity and hence of the chiral transition independent of the choice of the potential for the kaons, which also can be fixed from the data. With both model parameters fixed by data form Si+Au collisions, we then can make a prediction for the behavior of the kaon spectra for Au+Au, which have already been taken and are in the process to be analyzed [27].

In fig. 3 we show our result for the kaon production data for Si+Au. Together with the data, we also show the prediction of the RQMD model [6] determined by the E-814 collaboration. In order to obtain reliable statistics, in our calculation the kaon spectrum has been obtained after averaging over rapidity, while the data are taken at somewhat forward rapidities. A detailed analysis of the rapidity dependence will be presented in a more extensive article[1]. Depending on whether or not the last data point is to be taken

[1] In our schematic model (section 2) we have checked that in the limit of a Bjorken type fireball, a soft component in the kaon spectrum can be obtained as well, provided the longitudinal expansion is not too rapid. Since at AGS energies the fireball formed is somewhere between Bjorken-type and spherical, we a rather confident, that in a more extensive simulation, the overall picture will not be changed.

into account they are reproduced by a potential of $U_0 \simeq 50\,\mathrm{MeV}$. The parameters we needed for the Walecka model are

$$g_v = 5.5, \qquad g_s = 9.27 \tag{10}$$

which is to be compared with the original Walecka parameters which have been determined from fitting nuclear matter properties

$$g_v^{orig} = 11.56 \qquad g_s^{orig} = 9.27 \tag{11}$$

Notice that a smaller vector coupling than the original Walecka value is needed in order to reproduce the kaon data[2]. This is in qualitative agreement with our arguments for the attractive kaon potential, where also a reduced vector coupling is needed. Notice also, that a direct comparison with lattice gauge results for the energy density does not determine the vector coupling since it does not contribute at zero chemical potential. However, a comparison with measured baryon number susceptibilities from the lattice also requires a reduction of the vector coupling around T_c [18], and a more complete calculation will have to take the temperature dependence of the vector coupling as given by the lattice gauge data into account. In fig. 3 we also show the resulting kaon spectrum obtained without any mean field for the baryons. Clearly no soft component has developed in this case.

Finally, our prediction for the kaon spectrum in case of Au+Au. We simulate the Au+Au collision by assuming a fireball of radius 6.5 fm and with 350 baryons inside the fireball. In fig. 4 we show the resulting spectrum for this configuration. Again the spectrum develops a concave shape but at low $m_\perp$ the slope is not as steep as that for the smaller system, mainly because of the increased rescattering of the kaons in the bigger fireball.

Before we conclude we should mention, that in our calculation the protons also show a soft component at small transverse momentum with a slope parameter of $T \simeq 80\,\mathrm{MeV}$ which is not seen in experiment. We believe that this is an artifact of the simplification of our calculation, namely the fact that we have worked with a constant vector coupling. In a more realistic calculation, the vector coupling should increase once the system has gone through the chiral transition giving rise to additional repulsion in the late stage of the reaction. (The $g_v = 5.5$ we have used is actually an average between the high temperature $g_v \simeq 0$ and the low temperature Walecka value ($g_v^{Walecka} \simeq 11$)) This should give the nucleons an additional collective push which will eliminate the soft component in the proton spectra.

[2]There is actually some freedom in the choice of the couplings. Both g_s and g_v can be changed by about 25% without affecting the results, provided that their difference is kept at about the same value.

4 Conclusions and Outlook

In this article we have explained the observed cold component in the K^+ spectrum at AGS energy $Si + Au$ collisions by the E-814 collaboration by collective cooling. For the cooling mechanism to be successful we had to make three model assumptions. First, that the kaon feels an attractive potential in nuclear matter at temperature close to T_c. Second, that the expansion of the fireball created in the collision is slow, because the system has to go through the chiral phase transition. And third, that above T_c the coupling of the vector mesons is reduced. This reduced vector coupling would then also qualitatively explain the attractive kaon potential.

We have simulated the effect of the chiral transition on the expansion dynamics with a relativistic mean field model. In order to slow down the system sufficiently, we had to choose a vector coupling which is smaller than that extracted from zero temperature properties of nuclear matter. Having fixed the mean field parameters for the nucleons and kaons by comparing with the data for $Si + Au$, we have predicted the K^+ spectrum for the heavier system of $Au + Au$. Again the spectrum exhibits a concave shape but with a larger slope at small transverse mass than that of the small system ($Si + Au$). Also the fraction of soft kaons is somewhat reduced. This is simply a result of the more efficient rescattering in the bigger system, which knocks more kaons out of the soft component.

If the scenario presented in this article is correct, the smaller system of Si+Au seems to be better suited to study the effects of chiral symmetry restoration[3]. It would, therefore, be desirable if these measurements could be extended over a wider range in p_t and rapidity, such that the connection with the data of the E-802 collaboration can be made. In particular it would be extremely interesting to study the kaon spectra as a function of bombarding energy. Within our scenario we would predict that the soft component should disappear at lower bombarding energies, because the chiral symmetry restoration temperature is not reached and the kaons should not feel an attractive potential. But also at higher energies, the soft component eventually should disappear, because for temperatures much larger than T_c, when most of the glue is decondensed, the pressure increases to that of an ideal gas. As a consequence, the system expands rapidly and the necessary condition for adiabaticity is not fulfilled anymore.

Our present calculation will have to be improved in order to include a dynamical change of the vector coupling, which we have taken to be constant. In order to ensure energy and momentum conservation, the mean field model has to be modified. This modification will be guided by the lattice results on the baryon number susceptibility. This also will restrict the choice of mean field parameters and should cure the problem with the proton spectra. Furthermore, we are about to investigate, if the measurement of HBT correlations of the soft kaons could provide independent experimental information

[3] It may also be possible to create a smaller fireball by triggering on more peripheral Au+Au events.

about the long lifetime of the fireball.

In conclusion, we believe that the soft component in the kaon spectra may very well be the first observed signature for chiral restoration in the laboratory. The scenario presented in this article may also be applicable to CERN energy reactions, provided that the temperature reached is not to far above T_c. If this is the case, the analysis of ref. [12] has to be repeated and it may very well turn out that the observed soft pions at CERN are yet another result of the chiral restoration transition.

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References

[1] J. Stachel, *Nucl.Phys. A*, **566** (1994)183c.

[2] T. Abbot et al (E-802 Collaboration), *Phys.Rev.Lett.*, **64** (1990)847.

[3] T. Abbot et al (E-802 Collaboration), *Phys.Rev.Lett.*, **66** (1991)1567.

[4] S. Ahmad et al. (E-810 Collaboration), *Phys.Lett. B*, **281** (1992)29.

[5] T. Hemmick, *Nucl.Phys. A*, **566** (1994)435c.

[6] H. Sorge and H. Stöcker and W. Greiner, *Ann. Phys. (NY)*, **192** (1989)266.

[7] T.J. Schlagel, S.H. Kahana, and Y. Pang, *Phys.Rev.Lett.*, **69** (1992)3290.

[8] V. Koch, G.E. Brown, and C.M. Ko, *Phys.Lett. B*, **265** (1991)29.

[9] E. Shuryak, *Nucl.Phys. A*, **553** (1991)814.

[10] L. Xiong and C.M. Ko and V. Koch, *Phys.Rev. C*, **47** (1993)788.

[11] X.S. Fang, C.M. Ko, G.E. Brown, and V. Koch, *Phys.Rev. C*, **47** (1993)1679.

[12] V. Koch and G.F. Bertsch, *Nucl.Phys. A*, **552** (1993)591.

[13] V. Koch and G.E. Brown, *Nucl.Phys. A*, **560** (1993)345.

[14] M. Lutz, A. Steiner, and W. Weise, *Regensburg Preprint TPR-93-19*, (1993).

[15] C.H. Lee, H. Jung, D.P. Min, and M. Rho, (1994); preprint SNUTP-93-81.

[16] C.B. Dover and G.E. Walker, *Phys.Rep.*, **89** (1982)1.

[17] A.E. Nelson and D.B. Kaplan, *Phys.Lett. B*, **192** (1987)193.

[18] T. Kunihiro, *Phys.Lett. B*, **271** (1991)395.

[19] G.E. Brown and M. Rho, *Stony Brook preprint*, (1994).

[20] B. Blättel and V. Koch and U. Mosel, *Rep. Prog. Phys*, **56** (1993)1.

[21] G. F. Bertsch and S. Das Gupta, *Phys.Rep.*, **160** (1988)189.

[22] P. Danielewicz and G.F. Bertsch, *Nucl.Phys. A*, **553** (1991)712.

[23] C.M. Ko, *Phys.Rev. C*, **23** (1981)2760.

[24] J. Theis, G. Graebner, G. Buchwald, J. Maruhn, W. Greiner, and J. Polonyi, *Phys.Rev. D*, **28** (1983)2286.

[25] J.B. Kogut, D.K. Sinclair, and K.C.Wang, *Phys.Lett. B*, **263** (1991)101.

[26] S. Gottlieb, A. Krasnitz, U.M. Heller, A.D. Kennedy, J.B. Kogut, R.L. Renken, D.K. Sinclair, R.L. Sugar, D. Toussaint, and K.C. Wang, *Phys.Rev. D*, **47** (1993)3619.

[27] E-814 collaboration, private communication

Figure captions:

Figure 1: Initial and final kaon spectra for different expansion times and fixed kaon potential at $U_0 = -50\,\mathrm{MeV}$. For orientation the data and RQMD results of the E-814 group are also shown. The calculated results are all in arbitrary units and are normalized such that the spectra have the same value at $m_\perp - m = 0$.

Figure 2: Initial and final kaon spectra for different kaon potentials and fixed expansion time $\tau = 10\,\mathrm{fm/c}$. For orientation the data and RQMD results of the E-814 group are also shown. The calculated results are all in arbitrary units and are normalized such that the spectra have the same value at $m_\perp - m = 0$.

Figure 3: Kaon spectra from transport calculation. Full line is result including mean fields for Baryons and kaons. The dotted line is the result for kaon mean field only, no mean field for the baryons and the dashed line is the pure cascade result. The calculated results are all in arbitrary units.

Figure 4: Kaon spectra for Si+Au (full line) and our prediction for Au+Au (dotted line)